STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

FINITE ELEMENT ANALYSIS OF MECHANICALLY STABILIZED EMBANKMENT AND REINFORCED EARTH AT DUNSMUIR

Study Supervised by .... Raymond A. Forsyth, P.E.

Principal Investigator .... Joseph B. Hannon, P.E.

Co-Investigator .... Kenneth A. Jackura, P.E.

Report Prepared by .... Thang K. Le, P.E.

R. A. FORSYTH, P.E.
Acting Chief, Office of Transportation Laboratory

83-01

10-68

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO
CA-TL-83/01		

4. TITLE AND SUBTITLE	5. REPORT DATE
FINITE ELEMENT ANALYSIS OF MECHANICALLY STABILIZED EMBANKMENT AND REINFORCED EARTH AT DUNSMUIR	February 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
T. K. Le, K. A. Jackura and J. B. Hannon	19302-643353
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NO
Office of Transportation Laboratory California Department of Transportation Sacramento, California 95819	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT & PERIOD COVERED
California Department of Transportation Sacramento, California 95807	Final
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Work described herein was performed in connection with the research project, "Install a New Static Finite Element Computer Program".

16. ABSTRACT

This report presents a comparison between theoretical stress-strain obtained by finite element analysis and measured stress-strain obtained by field instrumentation of two mechanically stabilized embankments (MSE) and a proprietary Reinforced Earth (RE) wall constructed on Interstate 5 at Dunsmuir.

Theoretical stress-strain values for soil and steel reinforcement elements agree reasonably well with field data.

The "General Two Dimensional Soils and Reinforced Soil Analysis Program" has been satisfactorily modified for use in evaluating the MSE and RE systems.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Finite element, reinforced earth, mechanically stabilized embankment, bar-mat reinforcement, steel strips, stress, strain, hyperbolic stress-strain relationship, instrumentation	No Restriction

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

The State of California does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mmm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2) acres	.09290 .4047	square metres (m^2) hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) kips (1000 lbs)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (ft-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi $\sqrt{in}$)	1.0988	mega pascals $\sqrt{metre}$ (MPa $\sqrt{m}$)
	pounds per square inch square root inch (psi $\sqrt{in}$)	1.0988	kilo pascals $\sqrt{metre}$ (KPa $\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

ACKNOWLEDGEMENTS

The authors wish to thank the personnel of the Headquarters Structural Research Unit who installed and modified the finite element computer program. Appreciation is also extended to all personnel of the Soil Mechanics and Pavement Branch who assisted in analyzing data and preparing the report. Special appreciation is extended to Peter Mundy who worked on the initial phases of this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

LIST OF TABLES

INTRODUCTION

Between 1974 and 1976 two mechanically stabilized embankments (MSE) and one Reinforced Earth (RE) embankment were constructed and instrumented on I-5 near Dunsmuir. The MSE walls were constructed with bar-mat reinforcement and concrete facing. The RE wall was constructed with smooth steel strip reinforcement and concrete facing. All three walls were instrumented to monitor their behavior. The results of the field study were reported in 1981(1),(2).

In 1977 a computer program called "General Two Dimensional Soils and Reinforced Soils Analysis"(12) was developed by Dr. L. R. Herrmann of the University of California at Davis in cooperation with Caltrans. As part of the study, the general two dimensional program was implemented to analyze stress and strain in soil reinforcement systems.

This report describes how the above program was utilized to evaluate and compare the behavior of the instrumented MSE and RE walls at Dunsmuir. It is the final report for the state financed research project, "Install a New Finite Element Computer Program".

Details of MSE and RE wall construction, field instrumentation, soil information, wall dimensions and properties of reinforcing and facing materials were reported by Chang, Hannon and Forsyth(1) in 1981.

Hyperbolic stress-strain relationships were used to take into account nonlinear, inelastic and stress-dependent behavior of soils.

The program listing and User's Manual that were used in the analysis are not included in this report but are available at the Caltrans Laboratory.

CONCLUSIONS

1. Theoretical stresses and strains in the soil and reinforcement elements given by the "General Two Dimensional Soils and Reinforced Soil Analysis Program" are comparable to the stresses and strains measured in the field for both the MSE and RE systems.

2. Applied procedures for MSE and RE in finite element analysis are quite similar. The friction factor and cohesion between soil and reinforcement in reinforced earth are actual friction and cohesion values obtained from laboratory pullout resistance tests with the same type of soil and steel strips used in the field. The friction factor and cohesion between steel and soil used in the analysis for MSE are equivalent factors converted from laboratory pullout resistance of bar-mat and surface area of longitudinal bars in the mat.

3. For meaningful results, all parameters for finite element analysis should be carefully established. Soil should be tested within the range of expected pressure and with the field density, water content and drainage conditions. Friction and cohesion between steel and soil, between soil and facings, etc., should be determined as accurately as possible.

4. The geometry of the finite element mesh and shape of elements have some effect on results, i.e., triangular elements in rectangular mesh tend to produce misleading results. Elements with one or two sides longer (3 times or greater) than the others tend to give inaccurate results. Connection points between fine grid and coarse grid elements should be kept far from the body of interest.

5. The computer program has been satisfactorily modified and tested and is now available for use.

RECOMMENDATIONS

The general two dimensional soils and reinforced soils analysis program should be utilized in the future to design and predict stress-strain behavior of earth and earth retaining structures.

Further testing of the program should be conducted with other instrumented reinforced soil structures (MSE, etc.) to further verify its effectiveness. All parameters for input into the finite element program should be carefully established to closely model field conditions.

Additional research is needed to establish stress-strain behavior of MSE systems under earthquake loading. A new computer program should be developed to simulate these conditions.

IMPLEMENTATION

Finite element computer programs are presently used within Caltrans to analyze stress-strain conditions of earth and earth related structures. The techniques presented in this report will be used by both the Transportation Laboratory and the Office of Structures to analyze MSE and RE systems. A program listing and User's Manual are available.

EVALUATION OF PARAMETERS

In order to use the finite element method for theoretical analysis of the MSE at Dunsmuir, hyperbolic stress-strain parameters were developed from results of triaxial shear and consolidation tests.

The parameters are listed as follows:

Parameter	
K, Kur	Modulus number
n	Modulus exponent
c	Cohesion intercept
ϕ	Internal angle of friction
R_f	Failure ratio
K_b	Bulk modulus number
m	Bulk modulus exponent

The hyperbolic stress-strain relationship was developed by Duncan for use in nonlinear incremental analysis of soil deformations(3). In each increment of such analyses the stress-strain behavior of the soil is assumed to be linear and the relationship between stress and strain is assumed to be governed by Hooke's Law of elastic deformation.

Stress-strain curves for soils can be approximated by hyperbolas represented by the following equation:

$$(\sigma_1-\sigma_3) = \frac{\varepsilon_a}{\frac{1}{E_i} + \frac{\varepsilon_a}{(\sigma_1-\sigma_3)_{ult}}} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where: E_i = initial tangent modulus
ϵ_a = axial strain
$(\sigma_1 - \sigma_3)_{ult}$ = value of stress difference which is related closely to the strength of soil.

Since an increase in confining pressure tends to result in a steeper stress-strain curve and a higher strength, the values of E_i and $(\sigma_1 - \sigma_3)_{ult}$ will, therefore, tend to increase with increasing confining pressure.

Janbu(4) suggested the following equation:

$$E_i = Kp_a \left(\frac{\sigma_3}{p_a}\right)^n \quad \text{.....................} \quad (2)$$

where: P_a is atmospheric pressure expressed in the same units as E_i and σ_3.

values of $(\sigma_1 - \sigma_3)_{ult}$ can be related to the peak deviator stress $(\sigma_1 - \sigma_3)_f$ in a given test by expression

$$(\sigma_1 - \sigma_3)_f = R_f(\sigma_1 - \sigma_3)_{ult} \quad \text{................} \quad (3)$$

with
$$(\sigma_1 - \sigma_3)_f = \frac{2c \cos\phi + 2\sigma_3 \sin\phi}{1 - \sin\phi} \quad \text{............} \quad (4)$$

Relationship Between Tangent Modulus and Stress

The instantaneous slope of the stress-strain curve is the tangent modulus E_t

where
$$E_t = \left[1 - \frac{R_f(1-\sin\phi)(\sigma_1 - \sigma_3)}{2c \cos\phi + 2\sigma_3 \sin\phi}\right]^2 Kp_a \left(\frac{\sigma_3}{p_a}\right)^n \quad \text{.......} \quad (5)$$

inelastic behavior represented by use of different modulus values for loading and unloading.

In the hyperbolic stress-strain relationship, the same value of unloading-reloading modulus E_{ur} is used for both unloading and reloading.

$$E_{ur} = K_{ur}\, p_a \left(\frac{\sigma_3}{p_a}\right)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Nonlinear volume change is accounted for by using constant bulk modulus, B

where $$B = \frac{\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3}{3\varepsilon_v} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

ε_v is volumetric strain

in triaxial test, $$B = \frac{(\sigma_1 - \sigma_3)}{3\,\varepsilon_v} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

B will increase with increasing confining pressure

when $$B = K_b\, p_a \left(\frac{\sigma_3}{p_a}\right)^m \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

In the absence of volume change measurements, bulk modulus can be calculated using data from consolidation tests as verbally suggested by Professor Duncan of University of California, Berkeley.

where $$B = \frac{(\Delta p + 2k_o\Delta p)}{3\Delta\epsilon_v} \quad \ldots\ldots\ldots\ldots\ldots (10)$$

Δp = an increase in consolidation pressure

$\Delta\varepsilon_v$ = a change in volumetric strain, in this case, it is also vertical strain due to change in consolidation pressure, Δp.

Hyperbolic parameter values for foundation and backfill materials for the MSE walls are summarized in Table 1.

Table 1 - Hyperbolic Parameters of Foundation and Backfill Materials at Dunsmuir

	K	Kur	n	Ø Degrees	C psf	Rf	m	Kb
Foundation	214	422	1.2	38	200	0.83	0.57	96
Backfill	960	960	-0.23	36	230	0.87	-0.59	375

Details of how these values were obtained are presented in Appendix A.

Modeling of Reinforcement

The reinforced soil mass behind the wall was modeled as a composite, homogeneous orthotropic material.

The steel bar-mat was modeled as longitudinal bars alone with friction factor and cohesion value derived from laboratory pullout resistance tests as though no transversal bars existed.

Based on the results of pullout tests performed with the same type of bar-mat and soil with approximately the same angle of internal friction, the equivalent friction factor was estimated to be 2.0 with a cohesion of 144 psf. Friction factor between the smooth steel strip and soil used for the RE system was 0.6.

In MSE finite element analysis, the reinforcing was assumed to consist of two components; (1) the bar-mats and (2) the connection bolts between the bar-mats and the reinforced concrete facings.

For the RE wall, the reinforcing-soil mass was modeled for two areas that differed in their ratios of volume of reinforcement to volume of soil and surface area of steel per unit volume of soil. This was necessary because the cross-section analyzed consisted of both half and full facing panels. However, the number of steel strips was the same.

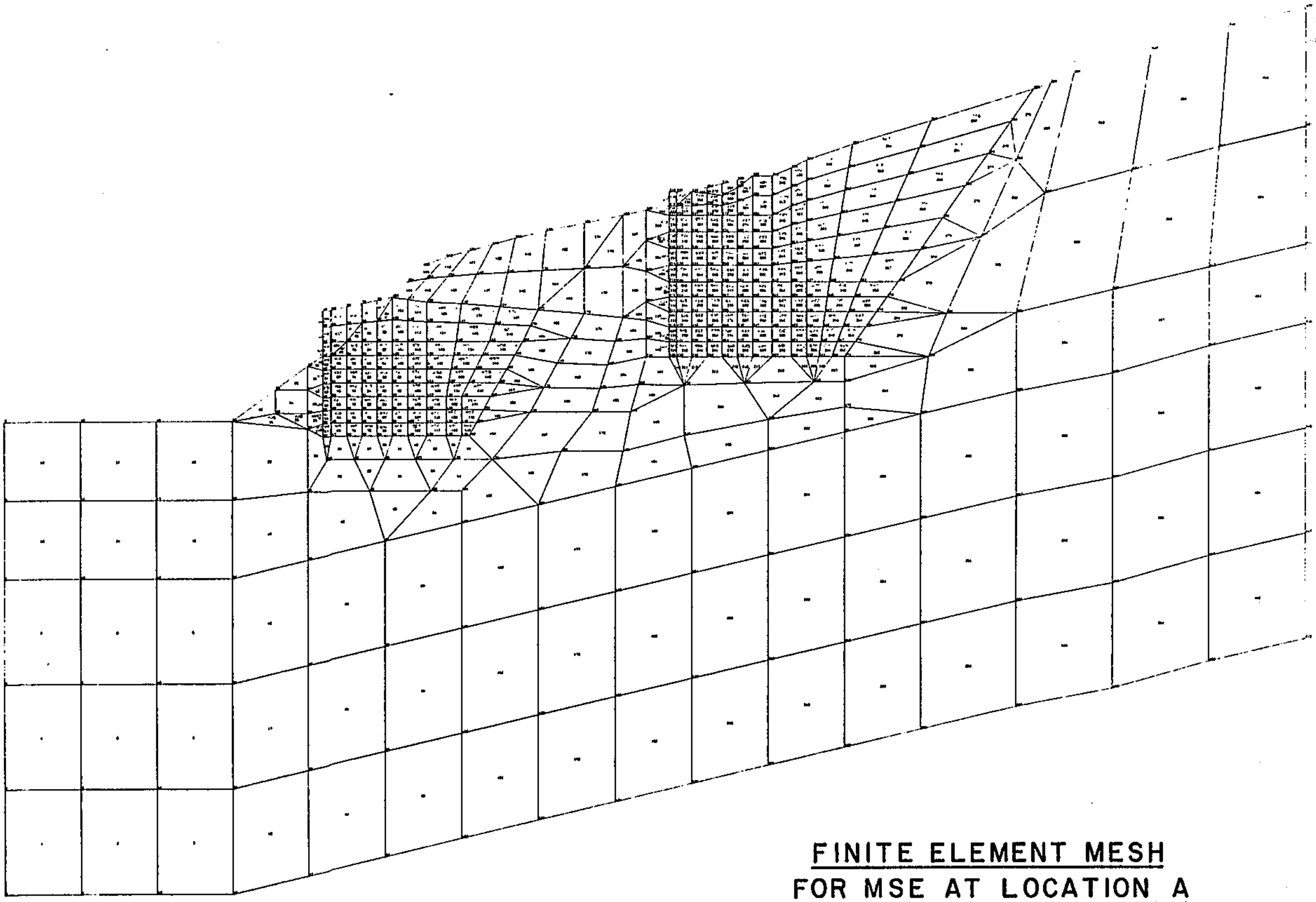
Theoretical Analysis by Finite Element Method

Dr. Herrmann's finite element analysis computer program, which was evaluated in this study, permits the analysis of stresses and strains in embankments, reinforced earth walls, sheet pilings and almost any other type of soil structure problem.

Finite Element Mesh Model

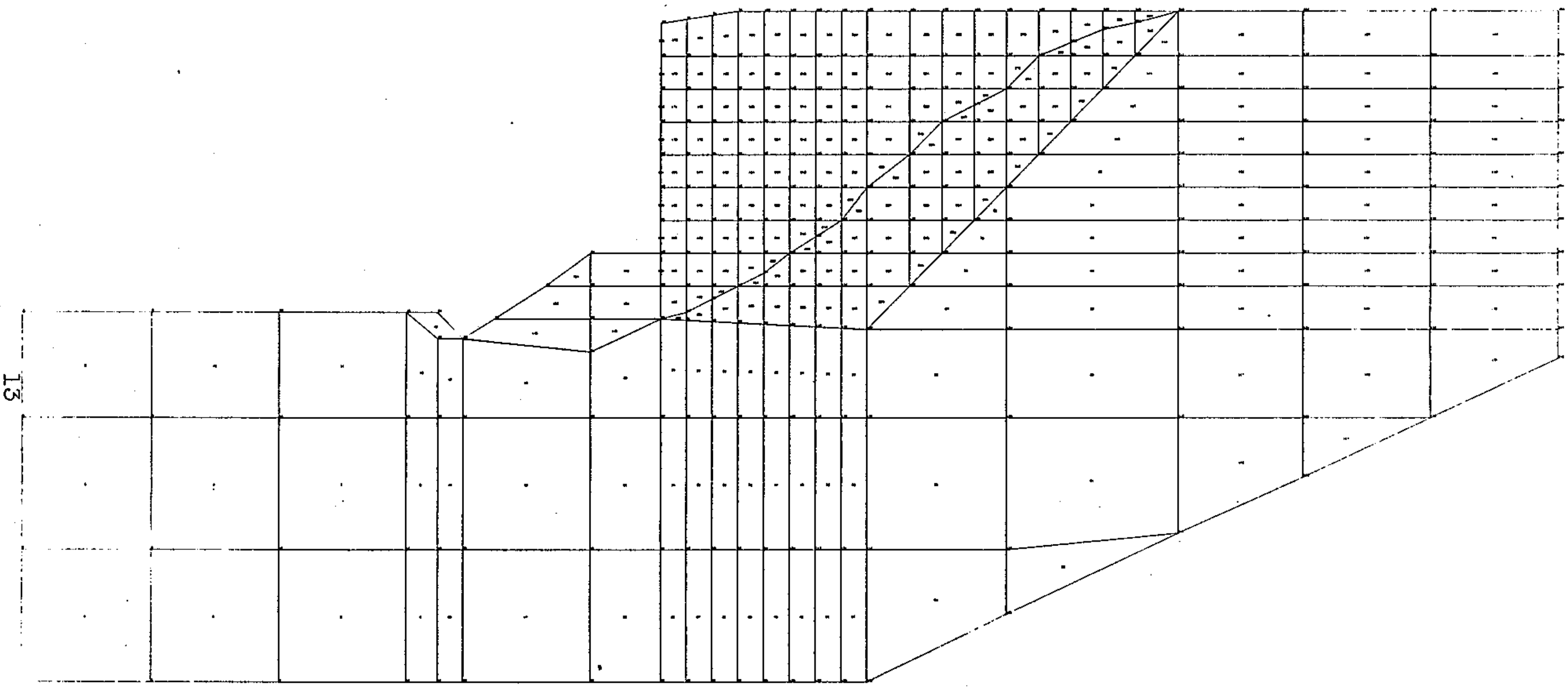
Meshes of finite elements were designed in such a way that the reinforced sections for the two MSE walls and the RE wall (bodies of interest) have a rather fine mesh. The mesh size increases with distance from the walls. The finite element meshes for this study (Figures 1 and 2) represent a section at Station 168+80 for the MSE and Station 188+50 for the RE wall.

The lower boundary on rock foundation is assumed fixed with no deformation. The left and right vertical boundaries are considered to be on rollers allowing downward movement. All vertical boundaries are at least 30 feet from the walls so that the computed stress-strain in the embankment will not be influenced by the proximity of the mesh boundary.



FINITE ELEMENT MESH
FOR MSE AT LOCATION A

Figure 1



FINITE ELEMENT MESH
FOR RE LOCATION B

Figure 2

Incremental Analysis

To simulate construction progress of the walls, an incremental analysis was used. Twenty-three increments were used to analyze MSE. The first was used to initialize the stress state in the foundation material, the second increment was used to find the stress after excavation for the lower wall and the next 9 increments were used to construct the lower wall. The twelfth increment simulated excavation for the upper wall and the last 11 increments the upper wall construction.

Twelve increments were used to analyze the RE wall.

Excavation subsequently followed by backfilling was modeled by assigning two elements to the same space. The element representing the original soil was excavated prior to the increment in which the backfilled material was placed.

Modeling Facing Elements

The precast concrete facing was modeled as a flexible member. Because the facing is in compression, a relatively high failure strain was assumed. Full friction was assumed between the soil mass and concrete facing member. Due to the presence of bar-mat reinforcement, relative movement was not permitted between the facing member and the surrounding backfill soil. The reinforcing bar-mat connection to the concrete facing was considered rigid. Reinforcement and facing were also considered to move as a unit with no rotation of facing elements permitted. Slippage of reinforcement and edge effects were considered.

DISCUSSION

This section provides a comparison of theoretical results from finite element analysis with actual (measured) performance data from instrumentation installed during construction of both the MSE and RE walls. For details of instrumentation installation and monitoring, refer to Appendix B and Reference 1.

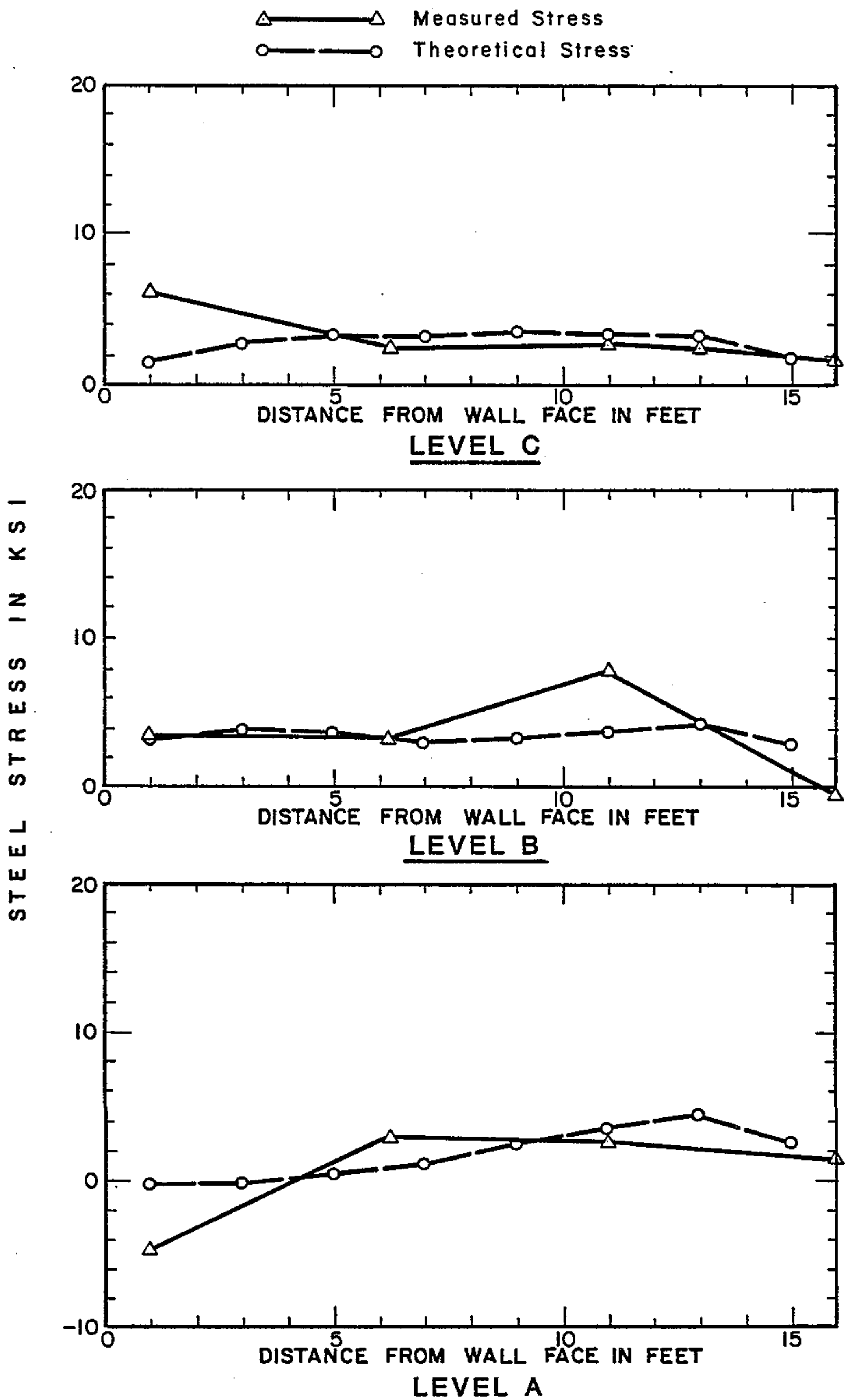
Soil Parameters - The foundation materials consist of silty clay founded on bedrock. Laboratory consolidated drained triaxial tests gave angles of internal friction varying from 28 to 45° and cohesion from 0 to 600 psf. The soil properties are quite varied and no clear separation exists between layers. Average properties were used and the foundation materials were considered as one type of soil.

Average modulus exponent from laboratory tests on undisturbed samples was estimated to be 1.2.

Backfill Material - Bulk modulus number and bulk modulus exponent of backfill material (lean sandy clay) were found to be -0.23 and -0.59. The negative exponent is uncommon for remolded drained tests. However, since a good relationship between E_i and σ_3 existed, the exponent was considered valid (Figure A3).

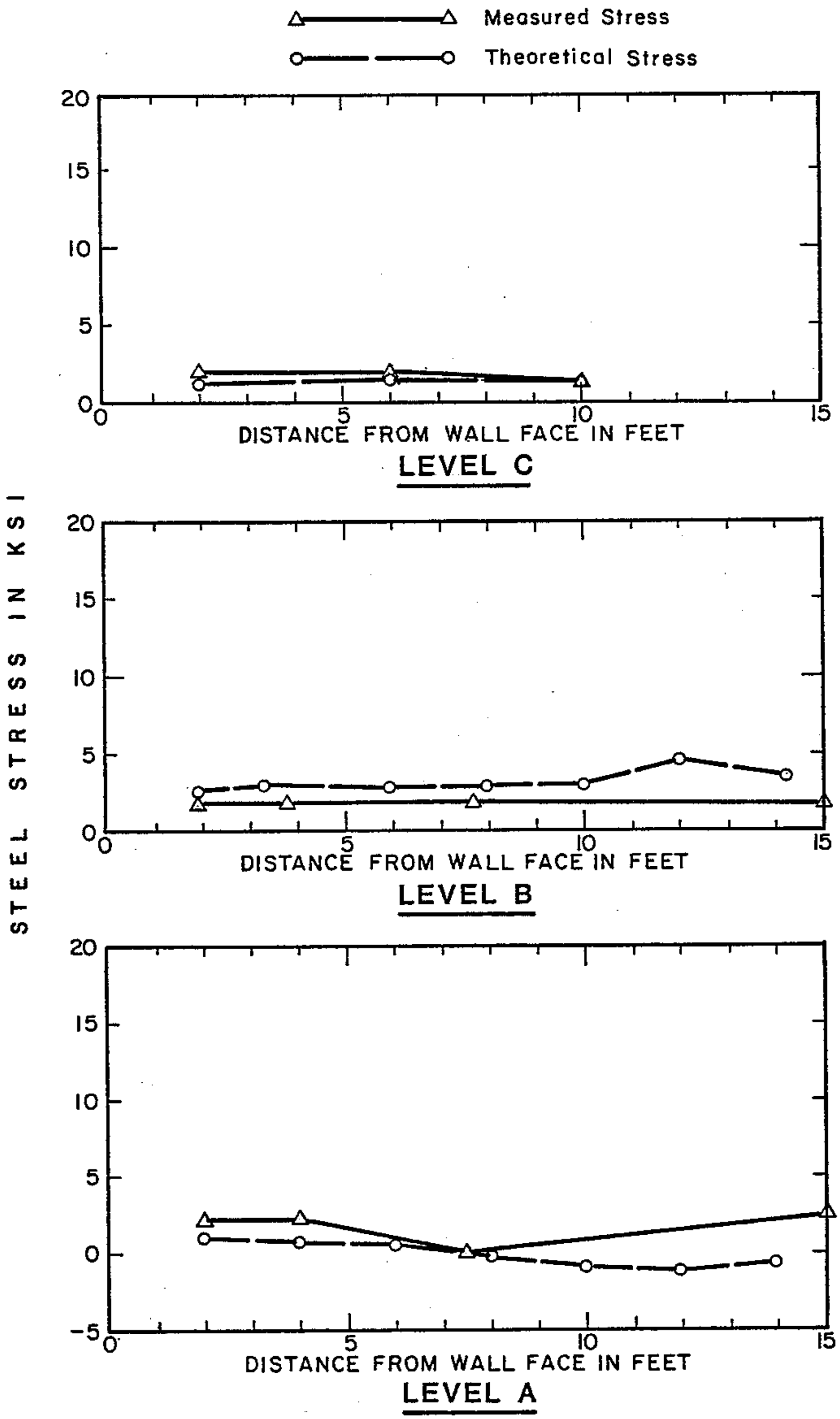
Stress in Steel Reinforcement

Figures 3 and 4 show stresses in steel reinforcement for the MSE and RE wall, respectively. In both cases, stresses given by finite element analysis are comparable to those measured by field instrumentation.



THEORETICAL AND MEASURED STEEL STRESSES IN RE WALL AT VARIOUS DISTANCES FROM FACE

Figure 3



THEORETICAL AND MEASURED STEEL STRESSES IN M.S.E. (UPPER WALL) AT VARIOUS DISTANCES FROM FACE

Figure 4

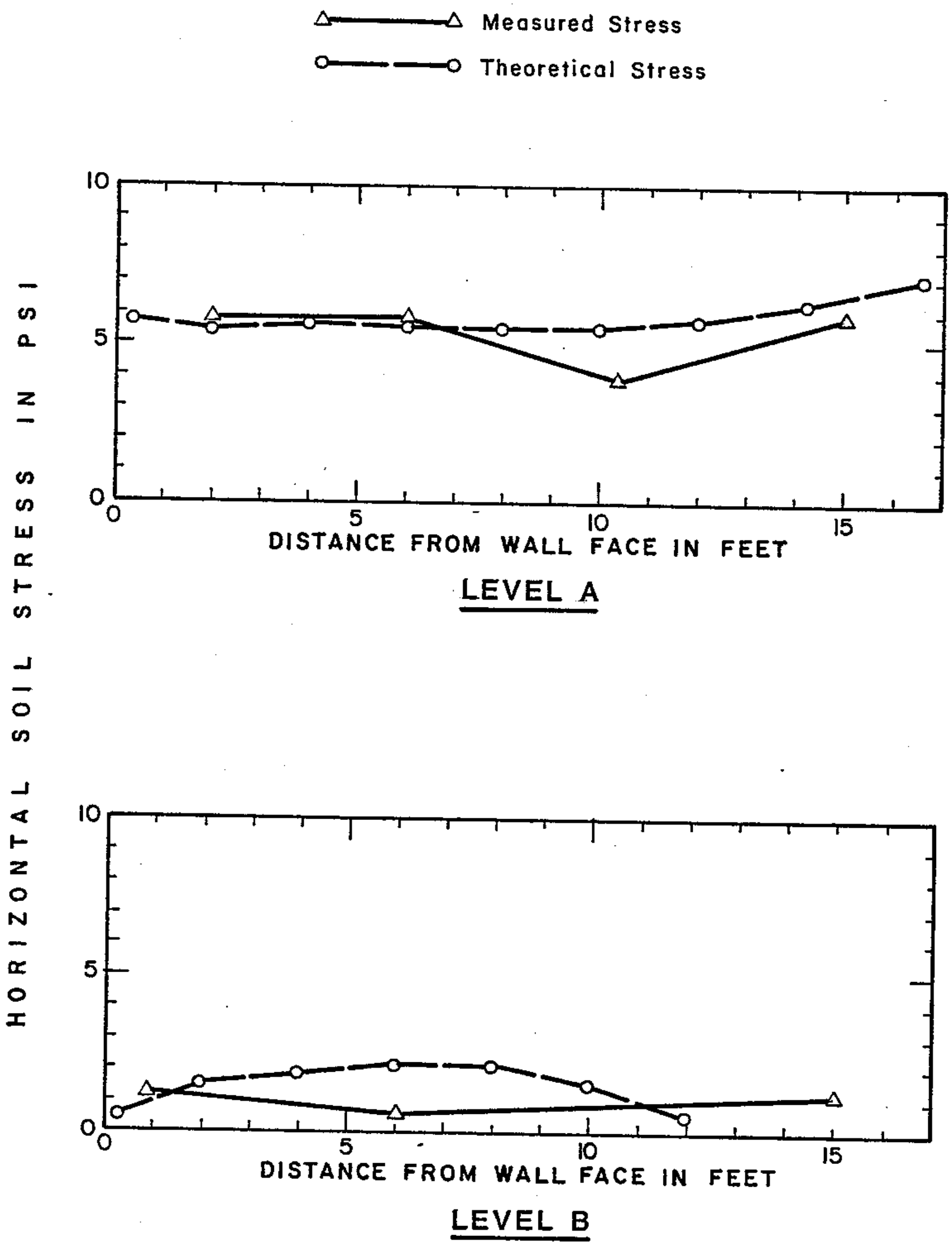
Vertical and Horizontal Stresses in Soil

Vertical and horizontal stresses in elements which match the location of field soil pressure cells are plotted on Figures 5 through 10.

In the upper MSE wall and in the RE wall, soil stresses correlate better for the after-stabilization stress condition (equilibrium). However, in the lower MSE wall, the measured and predicted soil stresses correlated more closely for the end of construction condition.

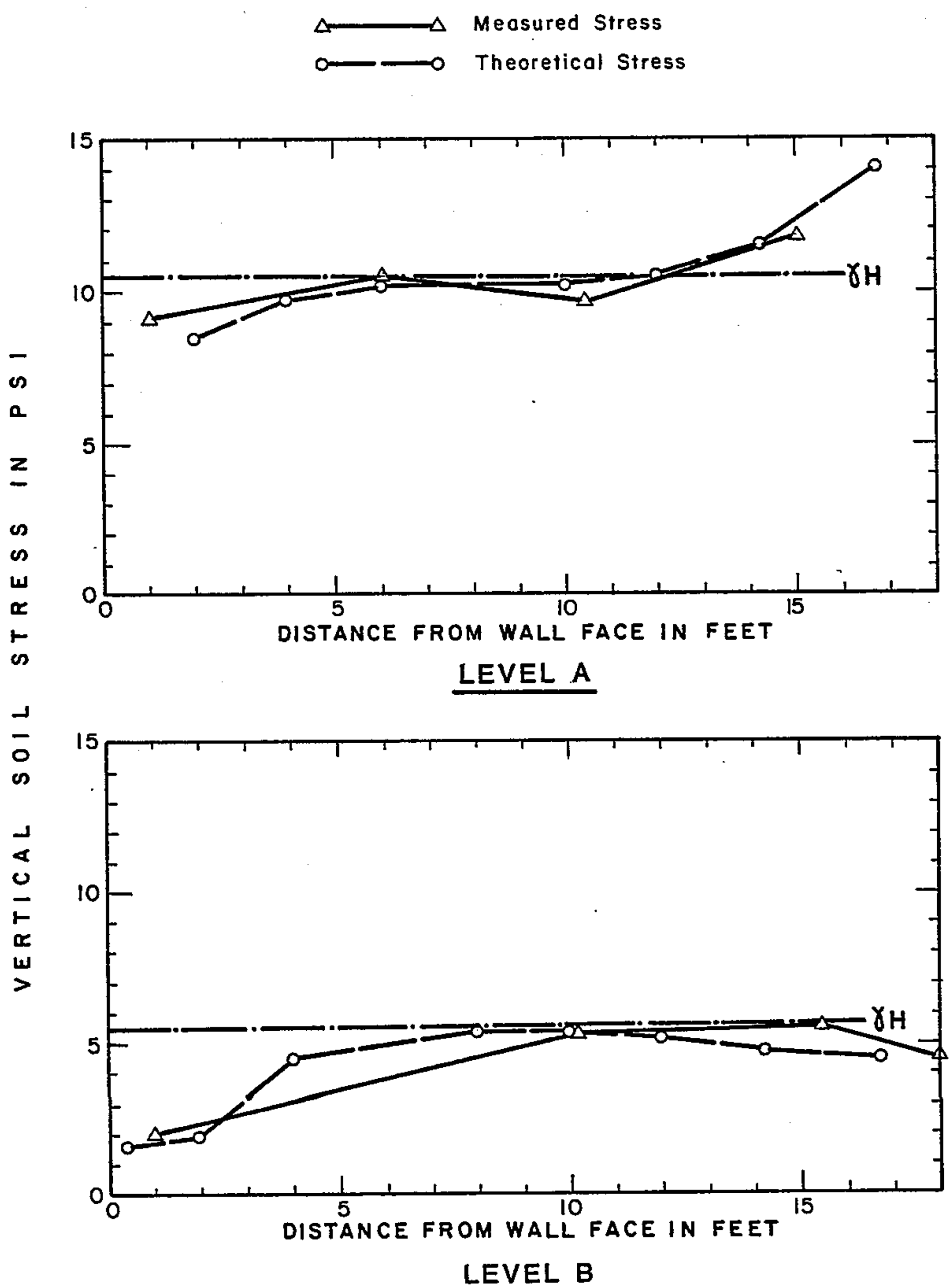
Settlement

Figure 11 shows plots of settlement for the RE wall at Levels A and B. It can be seen that both curves show an excellent correlation between measured and theoretical settlement.



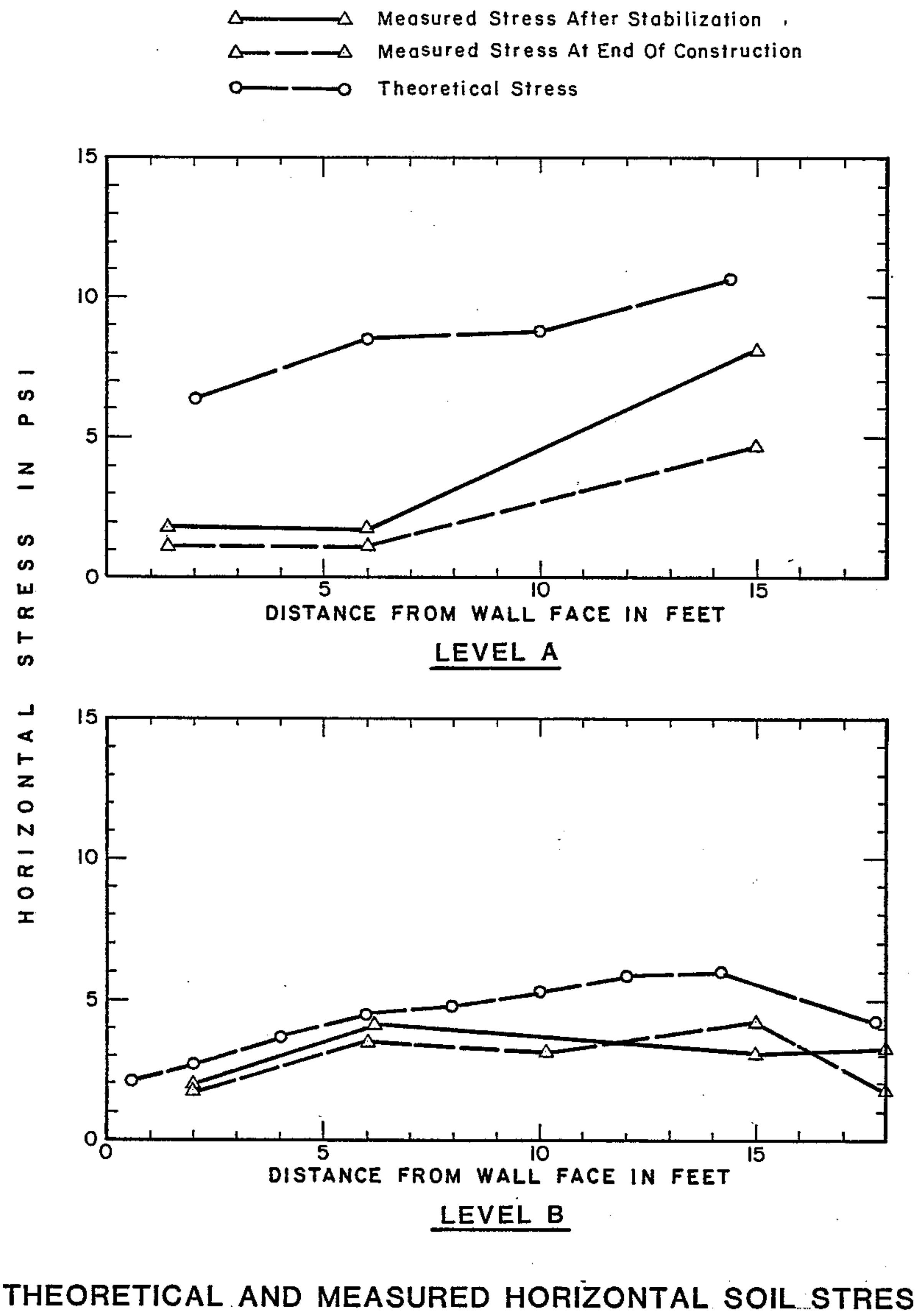
THEORETICAL AND MEASURED HORIZONTAL SOIL STRESSES IN M.S.E. (LOWER WALL) AT VARIOUS DISTANCES FROM FACE

Figure 5



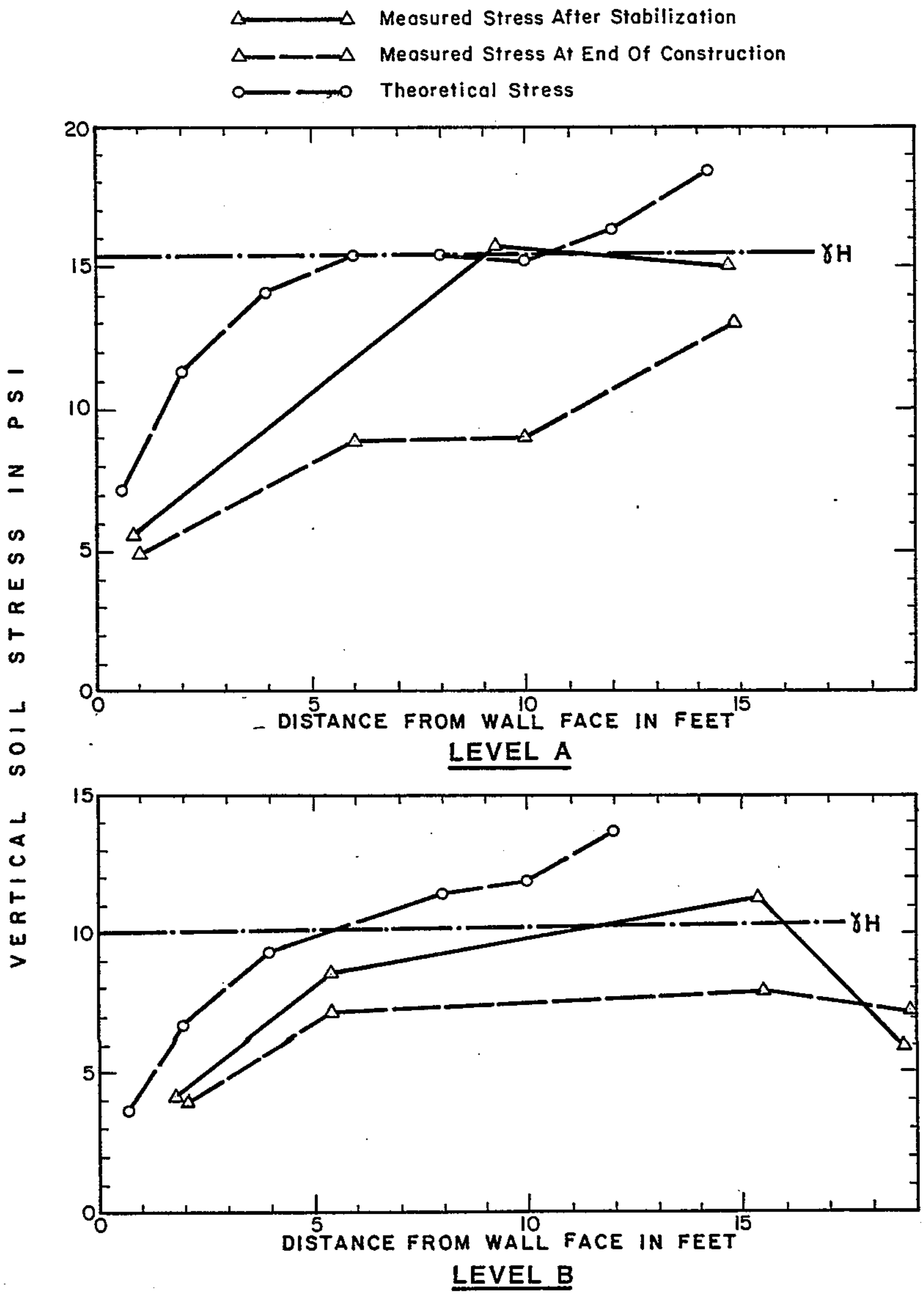
THEORETICAL AND MEASURED VERTICAL SOIL STRESSES IN M.S.E. (LOWER WALL) AT VARIOUS DISTANCES FROM FAC:

Figure 6



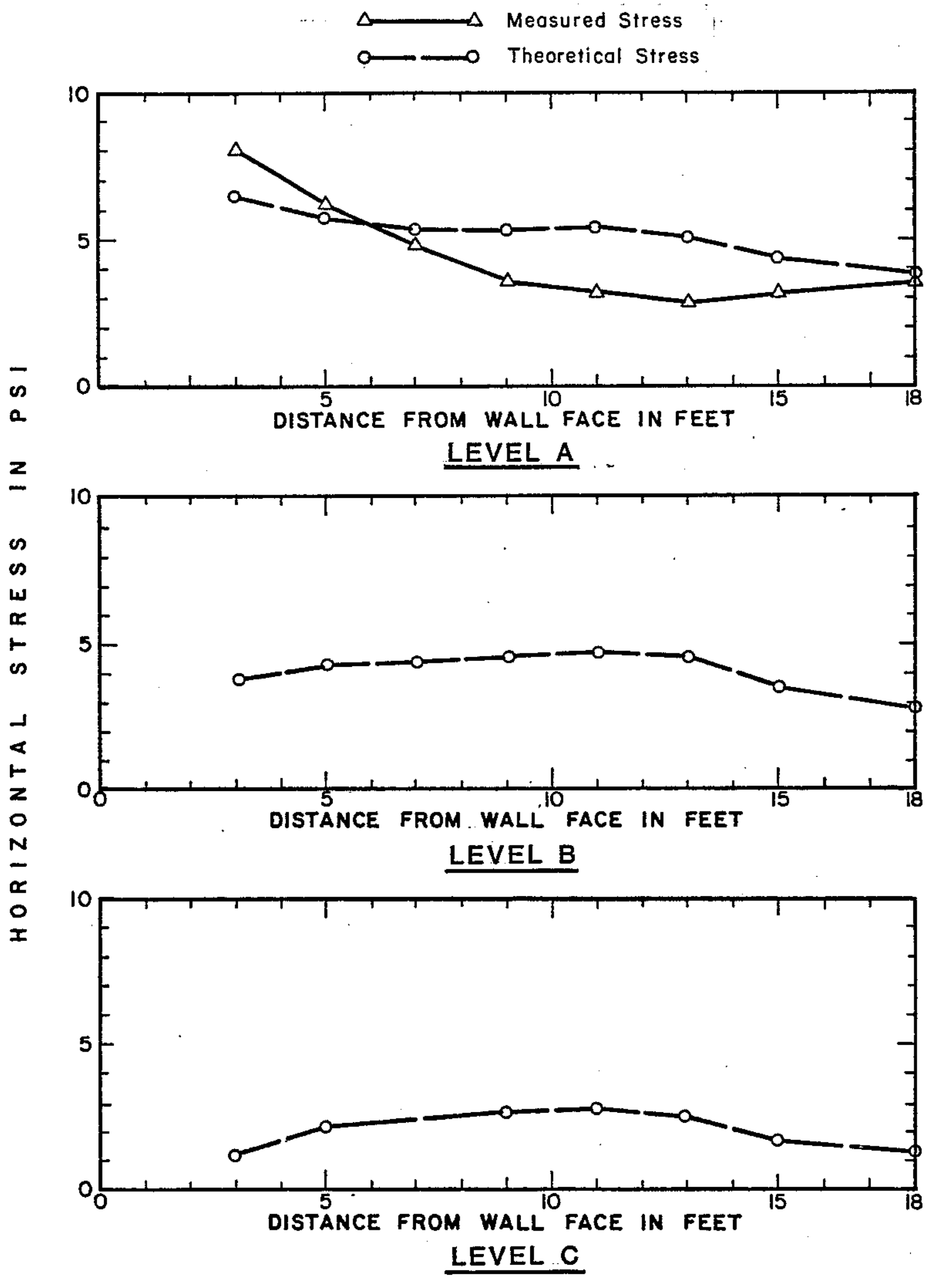
THEORETICAL AND MEASURED HORIZONTAL SOIL STRESSES IN M.S.E. (UPPER WALL) AT VARIOUS DISTANCES FROM FACE

Figure 7



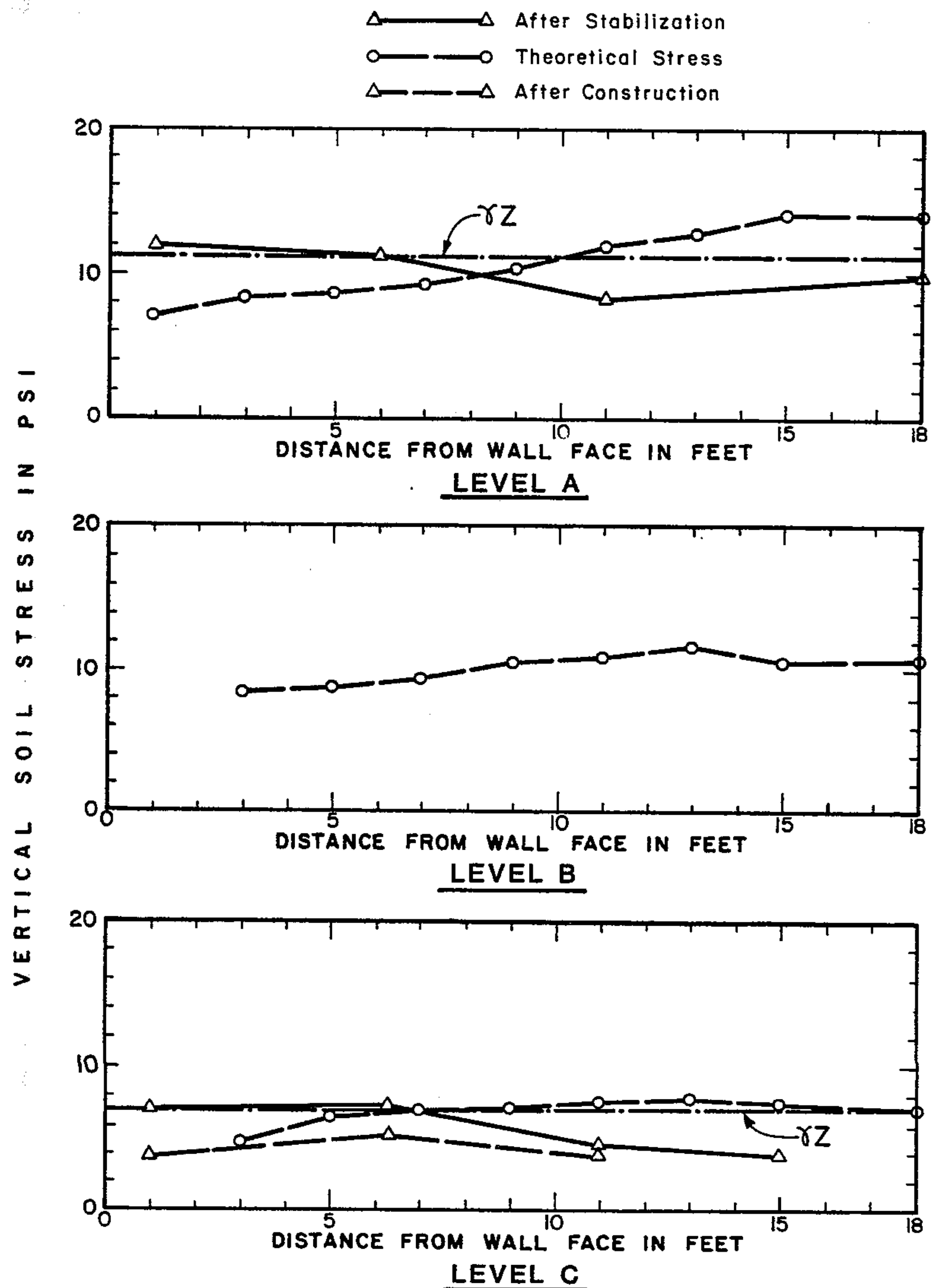
THEORETICAL AND MEASURED VERTICAL SOIL STRESSES IN M.S.E. (UPPER WALL) AT VARIOUS DISTANCES FROM FACE

Figure 8



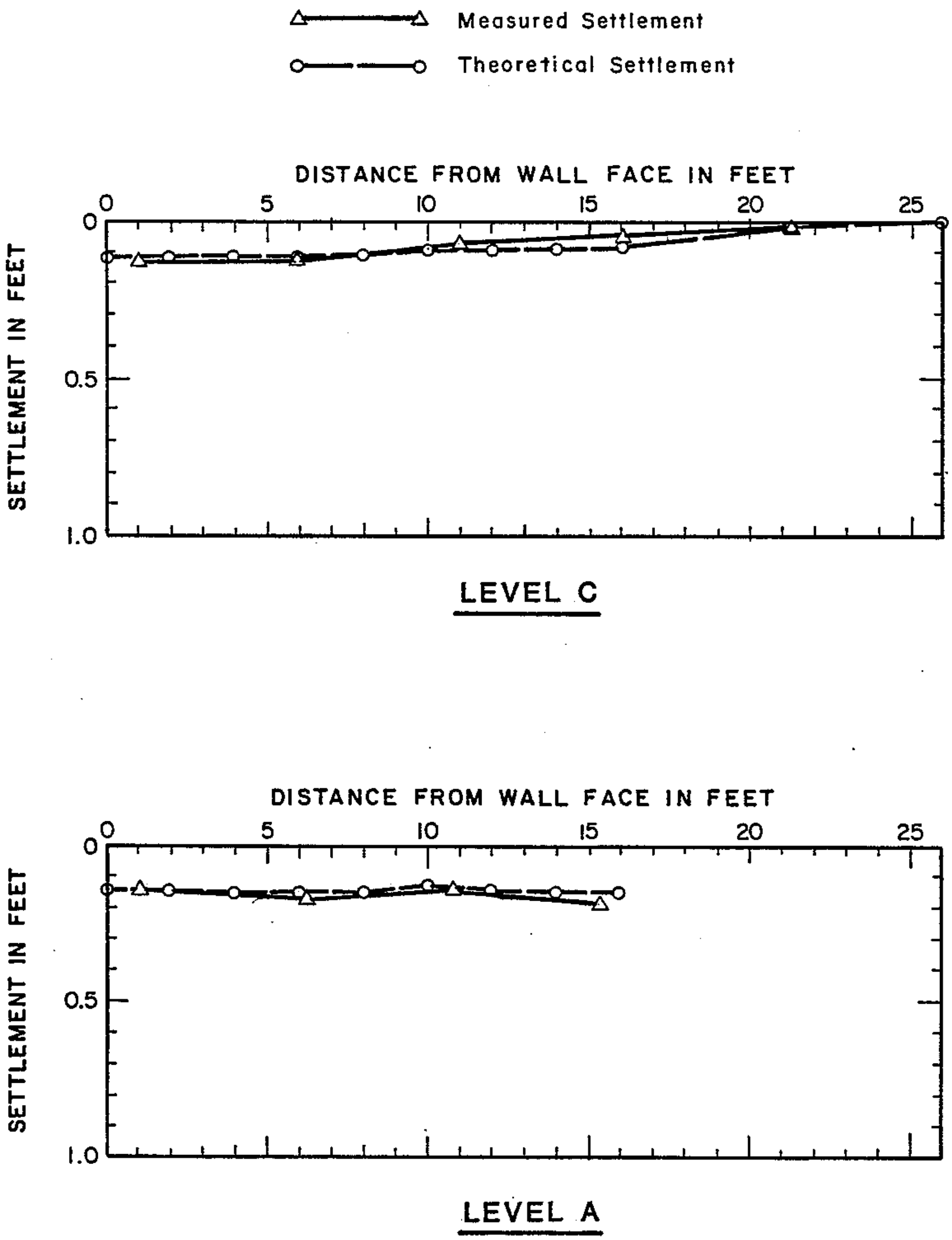
THEORETICAL AND MEASURED HORIZONTAL SOIL STRESSES IN RE. WALL AT VARIOUS DISTANCES FROM FACE

Figure 9



THEORETICAL AND MEASURED VERTICAL SOIL STRESSES IN R.E. WALL AT VARIOUS DISTANCES FROM FACE

Figure 10



THEORETICAL AND MEASURED SETTLEMENTS
IN RE WALL AT VARIOUS DISTANCES FROM FACE

Figure 11

REFERENCES

1. Chang, J. C, Hannon, J. B., and Forsyth, R. A., "Field Performance of Earthwork Reinforcement," Transportation Laboratory, Caltrans, Final Report 642155, June 1981.

2. Chang, J. C., Hannon, J. B., and Forsyth, R. A., "Field Performance Comparison of Two Earthwork Reinforcement Systems," Transportation Laboratory, Caltrans, Prepared for Presentation at 61st Annual Meeting of TRB, January 1982.

3. Duncan, J. M., Byrne, P., Wong, K. S., and Mabry, P., "Stress-Strain and Bulk Modulus Parameters for Finite Element Analysis of Stresses and Movements in Soil Masses," Report No. UCB/GT/78-02, April 1978.

4. Janbu, Nilmar, "Soil Compressibility as Determined by Oedometer and Triaxial Tests," European Conference on Soil Mechanics and Foundation Engineering, Wissbaden, Germany, Vol. 1, pp 19-25, 1963.

5. Herrmann, L. R., "Nonlinear Finite Element Analysis of Frictional Systems," Vol. 2, Proceedings of the International Conference on Finite Elements in Nonlinear Solids and Structural Mechanics, Gelo, Norway, August 1977.

6. Herrmann, L. R. and Al Yassm, Zayab, "Numerical Analysis of Reinforced Soil Systems", Proceedings of the ASCE Convention, April 1978.

7. Chang, J. C. and Forsyth, R. A., "Performance of a Reinforced Earth Fill," Transportation Research Report No. 510, Soil Mechanics, Transportation Research Board, National Research Council, Washington, D.C., 1974.

8. Chang, J. C. and Forsyth, R. A., "Design and Field Behavior of Reinforced Earth Wall," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. G77, Proc. Paper 13034, July 1977, pp. 677-692.

9. Romstad, K. M., Herrmann, L. R., and Shen, C. K., "Integrated Study of Reinforced Earth - I: Theoretical Formation," Journal of the Geotechnical Division, ASCE, Vol. 102, No. GT5, Proc. Paper 12144, May 1976, pp. 457-471

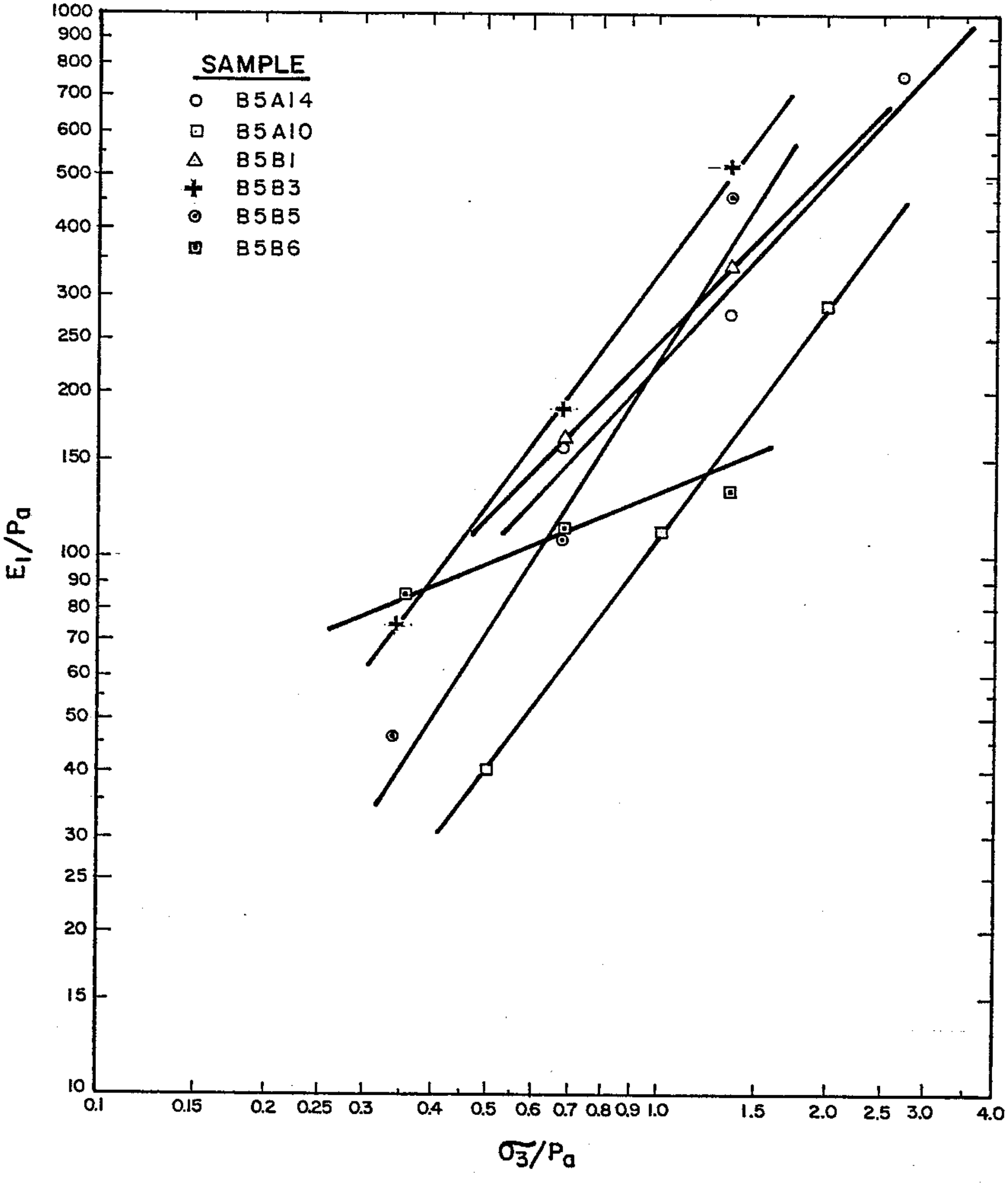
10. Shen, C. K., Romstad, K. M., and Herrmann, L. R., "Integrated Study of Reinforced Earth - II: Behavior and Design," Journal of the Geotechnical Engineering Division, ASCE, Vol. 102, No. GT6, June 1976.

11. Chang, J. C., "Earthwork Reinforcement Techniques," Transportation Laboratory, Caltrans, Final Report 632115, November 1974.

12. Herrmann, L. R., "General Two Dimensional Soils and Reinforced Earth Analysis Program," University of California, Davis, January 1978.

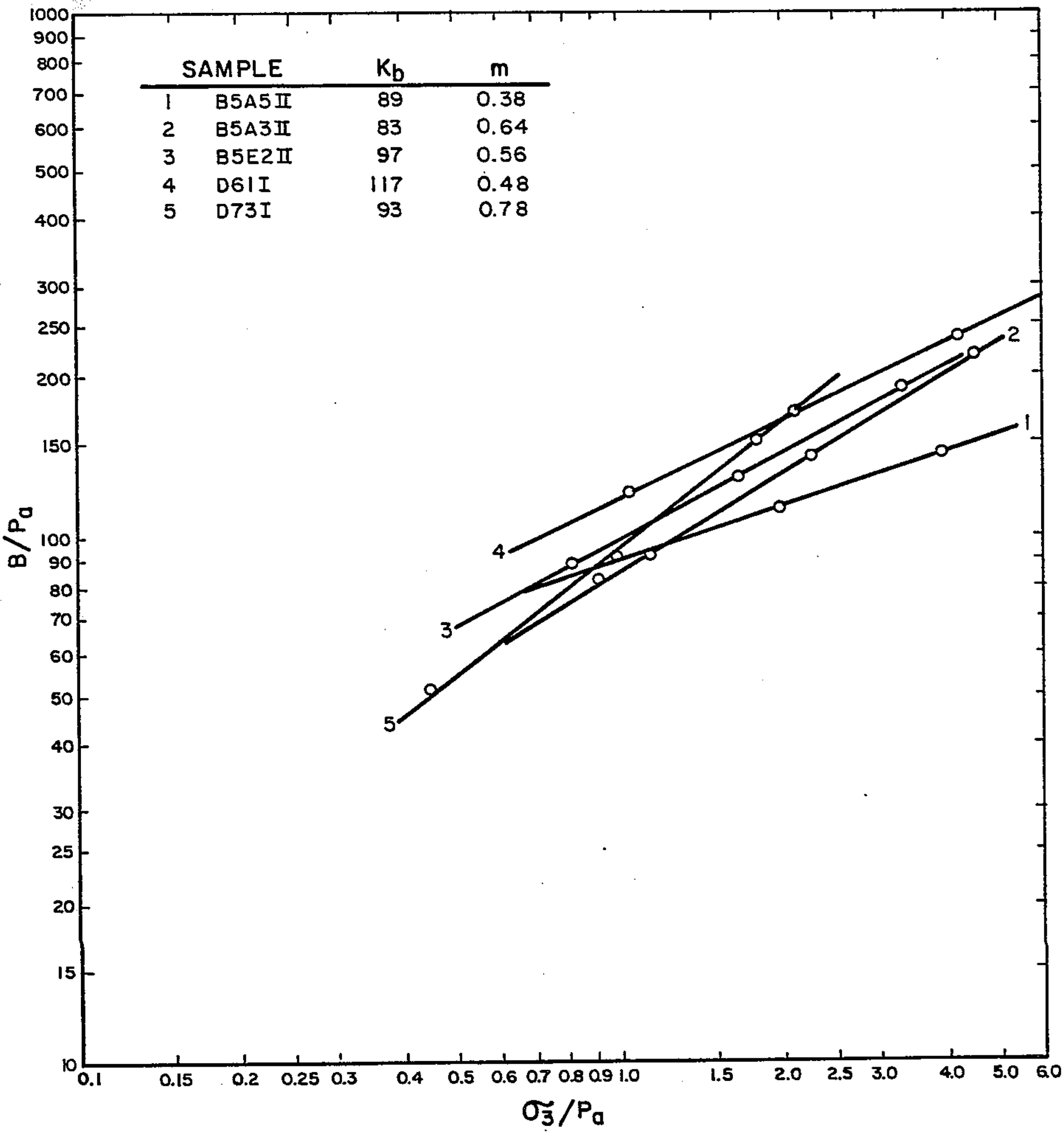
APPENDIX A

Hyperbolic Soil Parameters



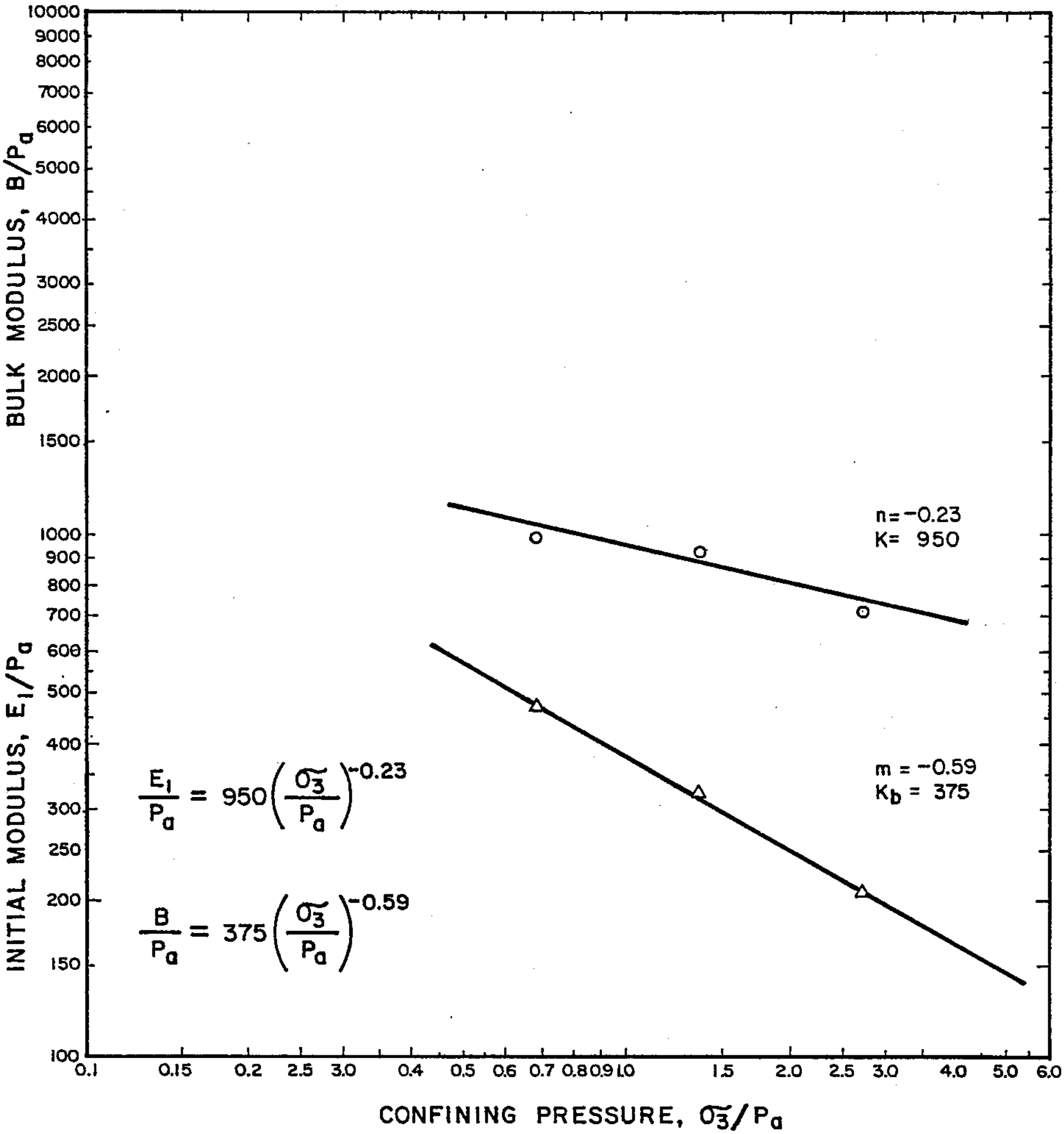
VARIATION OF TANGENT MODULUS WITH CONFINING PRESSURE FOR FOUNDATION MATERIAL

Figure 1A



VARIATION OF BULK MODULUS WITH CONFINING PRESSURE FOR FOUNDATION MATERIAL

Figure 2A



VARIATION OF INITIAL TANGENT MODULUS AND BULK MODULUS WITH CONFINING PRESSURE FOR BACK FILL MATERIAL

Figure 3A

Table IA - Modulus of Unloading-Reloading of Foundation Material from Consolidation Tests

Sample	σ_3/Pa	Eur / Pa	Kur
B5-A-3	2.03	499.57	213
B5-A-5	1.89	1222.35	569.43
B5-A-7	1.80	887.07	438.16
B5-A-10	1.65	494.51	271.14
B5-A-13	1.65	791.64	434.06
B5-B-2	1.42	951.83	558.59
B5-B-3	1.51	778.27	474.63
D-6-1	1.80	768.21	379.45
D-6-3	1.80	683.71	337.71
D-7-3	1.51	898.50	547.96
D-7-5	1.51	718.77	438.37

Table 2A - Bulk Modulus and Modulus Exponent of Foundation Material

Sample	K_b	m
B-5A-5II	89	0.38
B-5A-3II	83	0.64
B-5B-2II	97	0.56
D-6-1I	117	0.48
D-7-3I	93	0.78
Average	96	0.57

Table 3A - In-Place Nuclear Density of Embankment at Location A and B

	Station	Elevation (ft)	Density (pcf)
Location A	168 to 171	2471	123
	168 to 171	2476	119
	167 to 171	2477	122
Location B	185 to 188	2560	111
	187 to 190	2562	105
	185 to 188	2564	110
	188 to 190	2564	107
	185 to 188	2569	100
	188 to 190	2570	111

NOTE:

Average Density (pcf)	
Location A	Location B
121	107

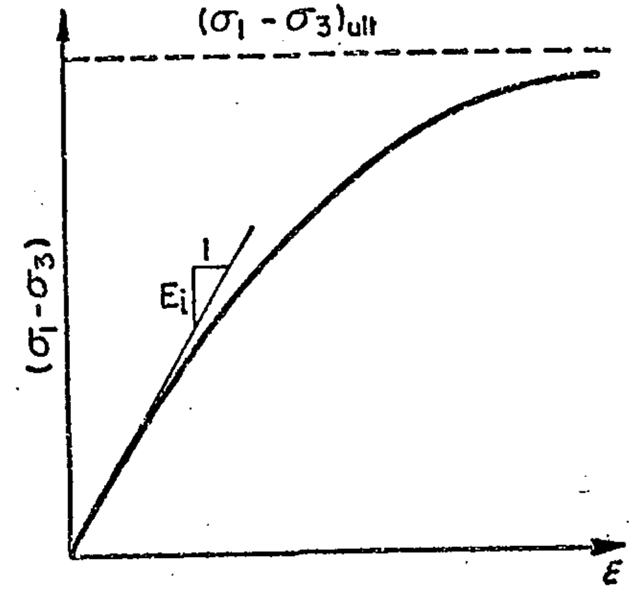
Table 4A - Summary of Properties of Backfill Material and Steel Reinforcement

A. Properties of Backfill Materials

Friction Angle,	ϕ_t ϕ_e	34° 36°
Cohesion, psf	C_t C_e	1000 200
Plasticity Index		5
pH		5.4
Resistivity, ohm.cm		8733
Sand Equivalent		36
Density, lb/ft^3		121

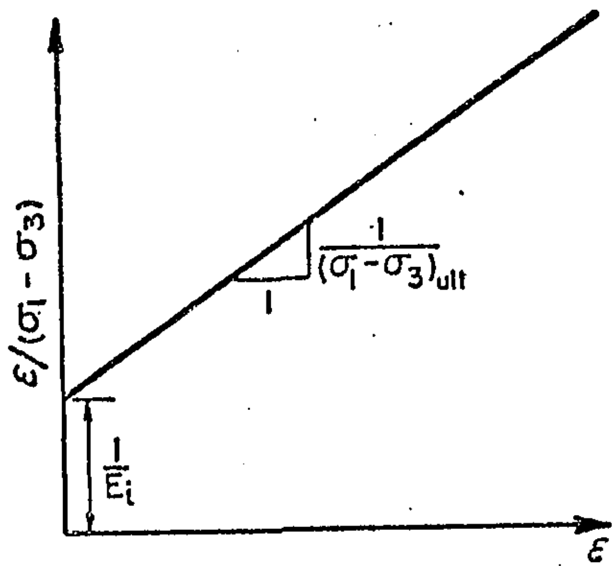
B. Properties of Steel

	MSE	RE
Elastic Modulus, ksi	29.3×10^3	28.0×10^3
Yield Stress, ksi	66.6	42.6
Ultimate Strength, ksi	95.2	62.6



REAL

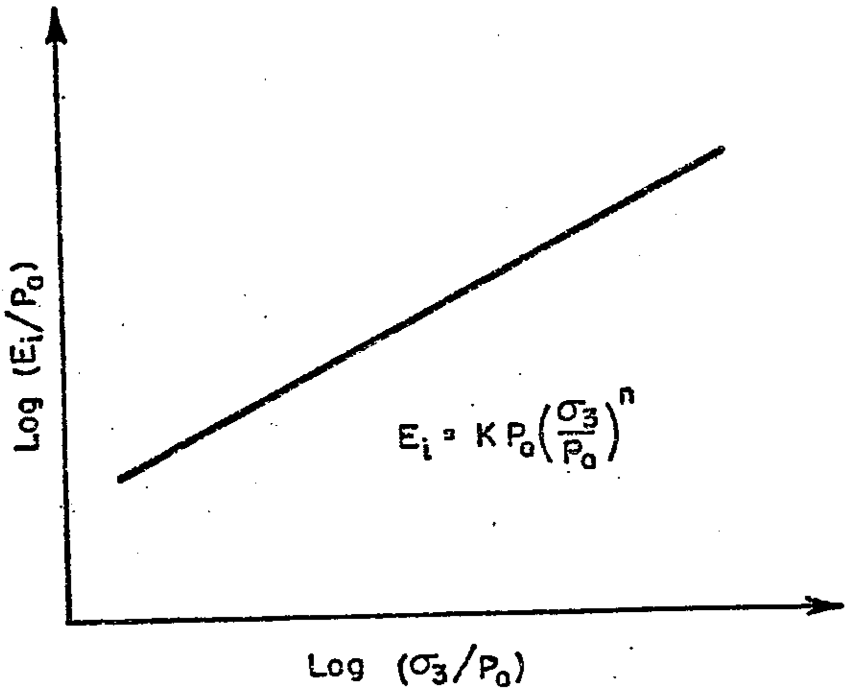
$$(\sigma_1 - \sigma_3) = \frac{\varepsilon}{\frac{1}{E_i} + \frac{\varepsilon}{(\sigma_1 - \sigma_3)_{ult}}}$$



TRANSFORMED

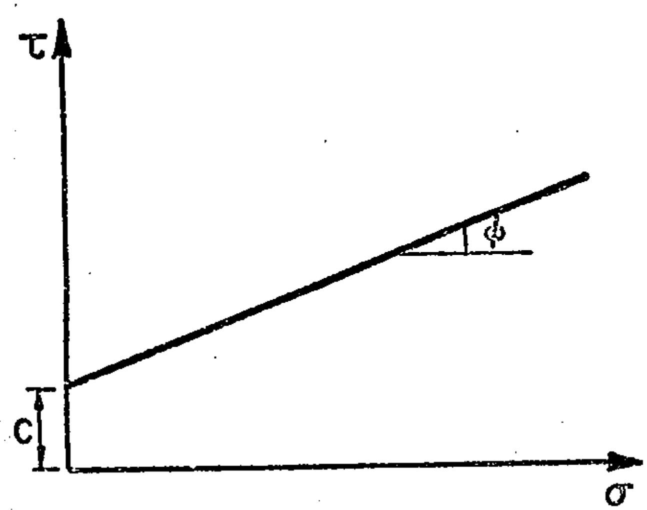
$$\frac{\varepsilon}{(\sigma_1 - \sigma_3)} = \frac{1}{E_i} + \frac{\varepsilon}{(\sigma_1 - \sigma_3)_{ult}}$$

HYPERBOLIC REPRESENTATION OF A STRESS-STRAIN CURVE (DUNCAN, 1978)



VARIATION OF INITIAL TANGENT MODULUS WITH CONFINING PRESSURE (DUNCAN, 1978)

Figure 5A

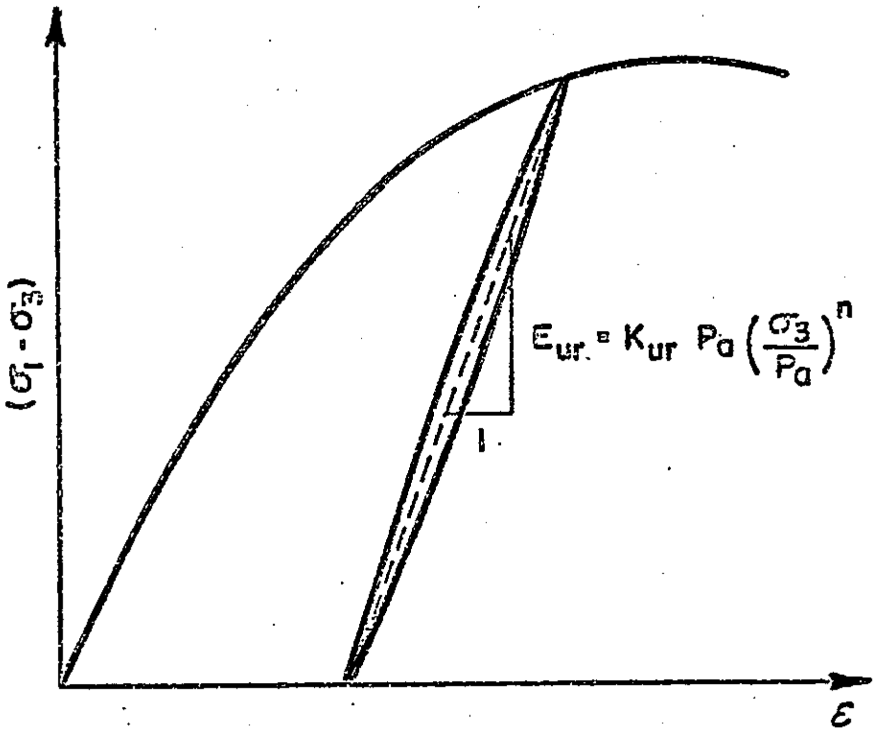


$$(\sigma_1 - \sigma_3)_f = \frac{2C\cos\phi + 2\sigma_3 \sin\phi}{1 - \sin\phi}$$

$$(\sigma_1 - \sigma_3)_f = R_f\,(\sigma_1 - \sigma_3)_{ult}$$

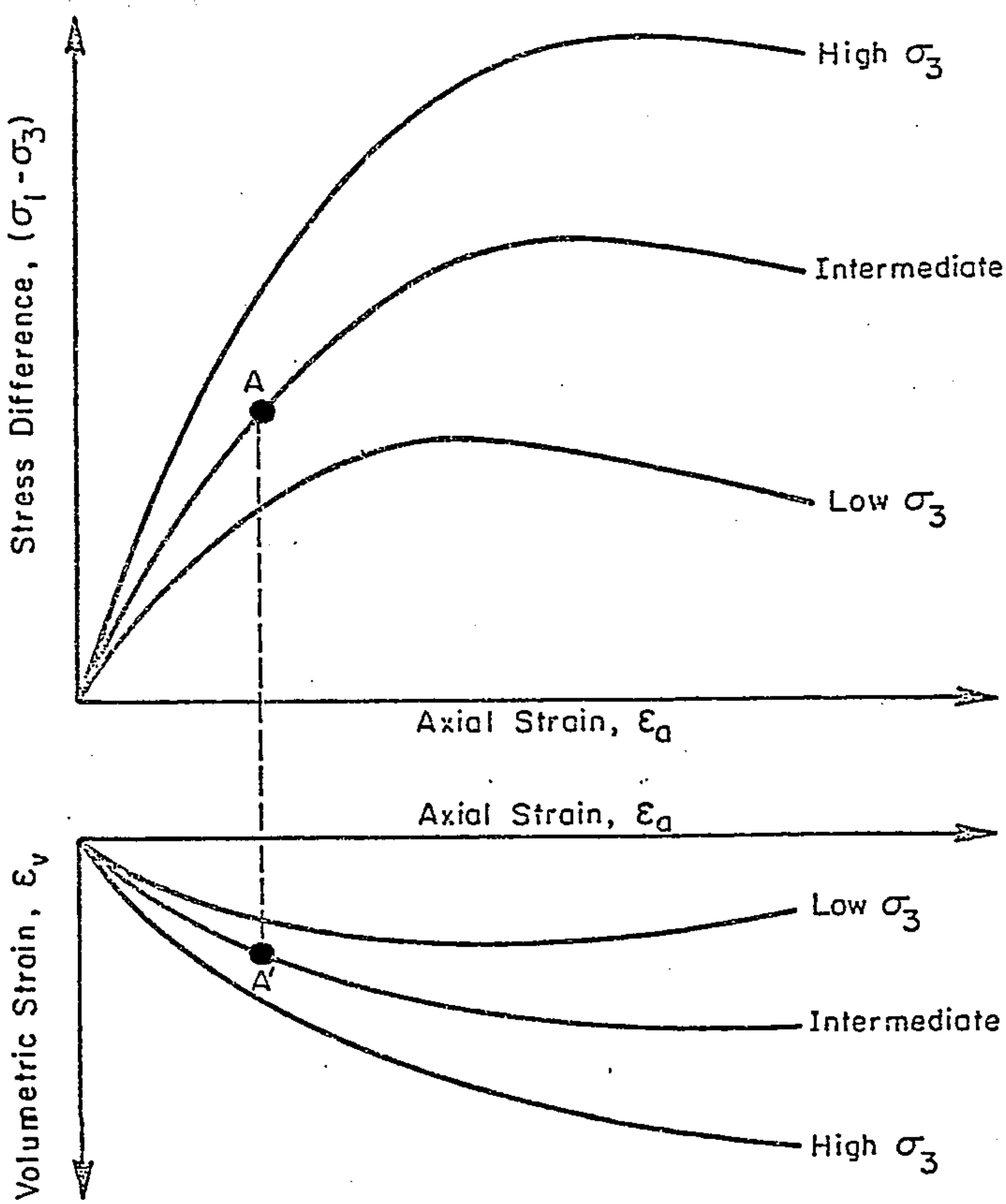
VARIATION OF STRENGTH WITH CONFINING PRESSURE (DUNCAN, 1978)

Figure 6A



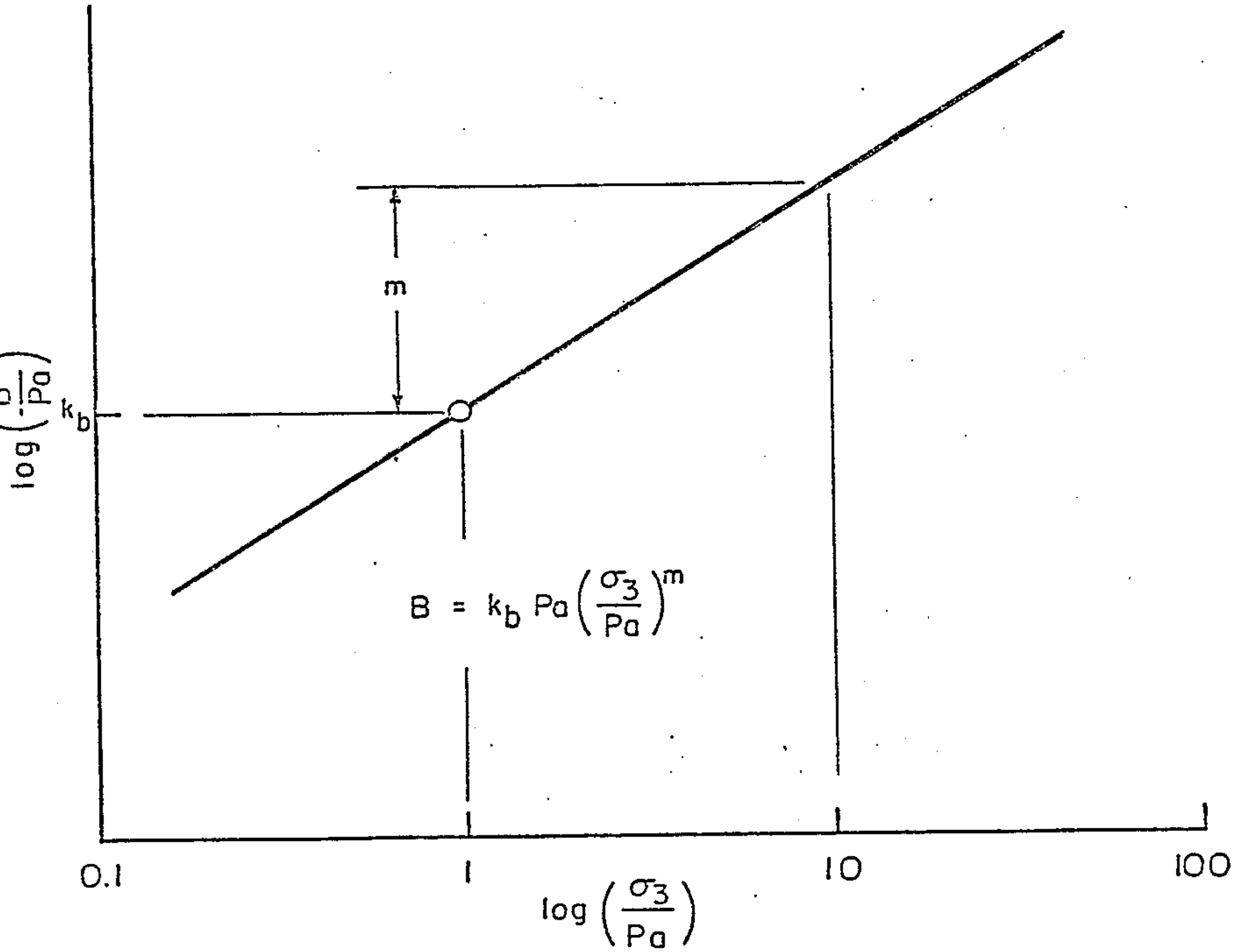
UNLOADING - RELOADING MODULUS
(DUNCAN, 1978)

Figure 7A



NONLINEAR AND STRESS-DEPENDENT STRESS-STRAIN AND VOLUME CHANGE CURVES (DUNCAN, 1978)

Figure 8A

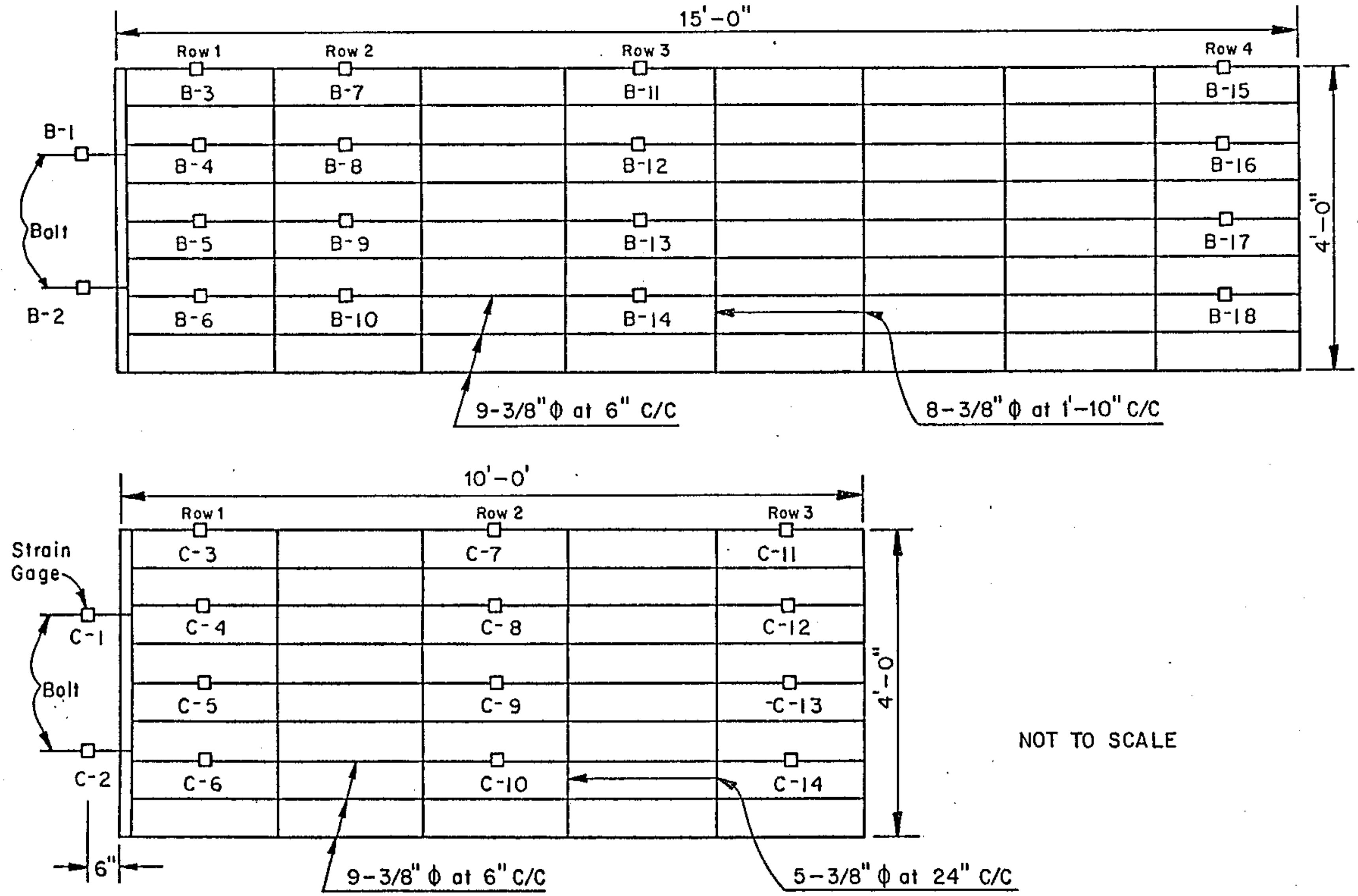


VARIATION OF BULK MODULUS WITH CONFINING PRESSURE
(DUNCAN, 1978)

Figure 9A

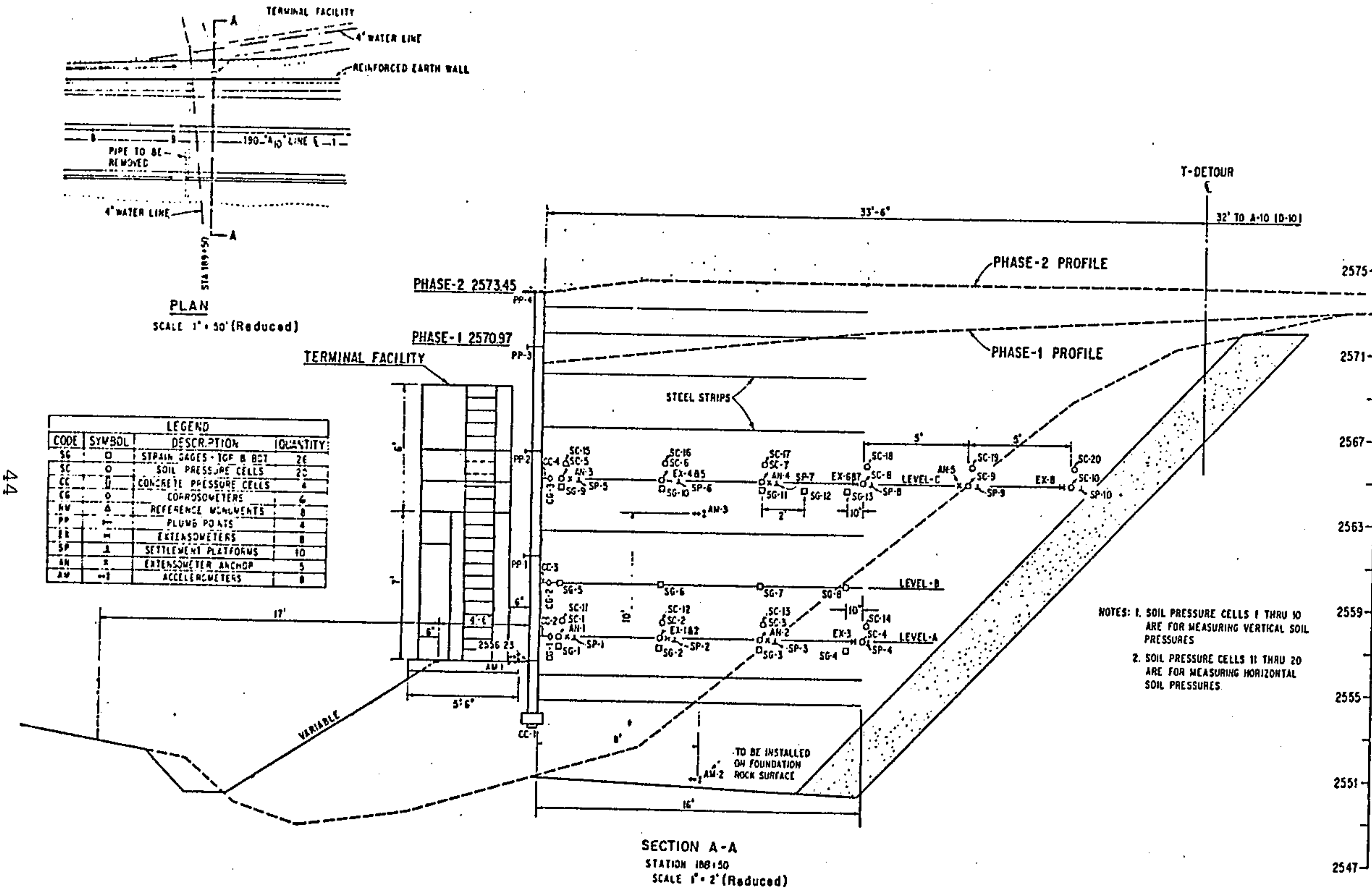
APPENDIX B

Reinforcement and Facing Members



INSTRUMENTED BAR-MAT, LEVEL B & C
UPPER WALL (MSE)

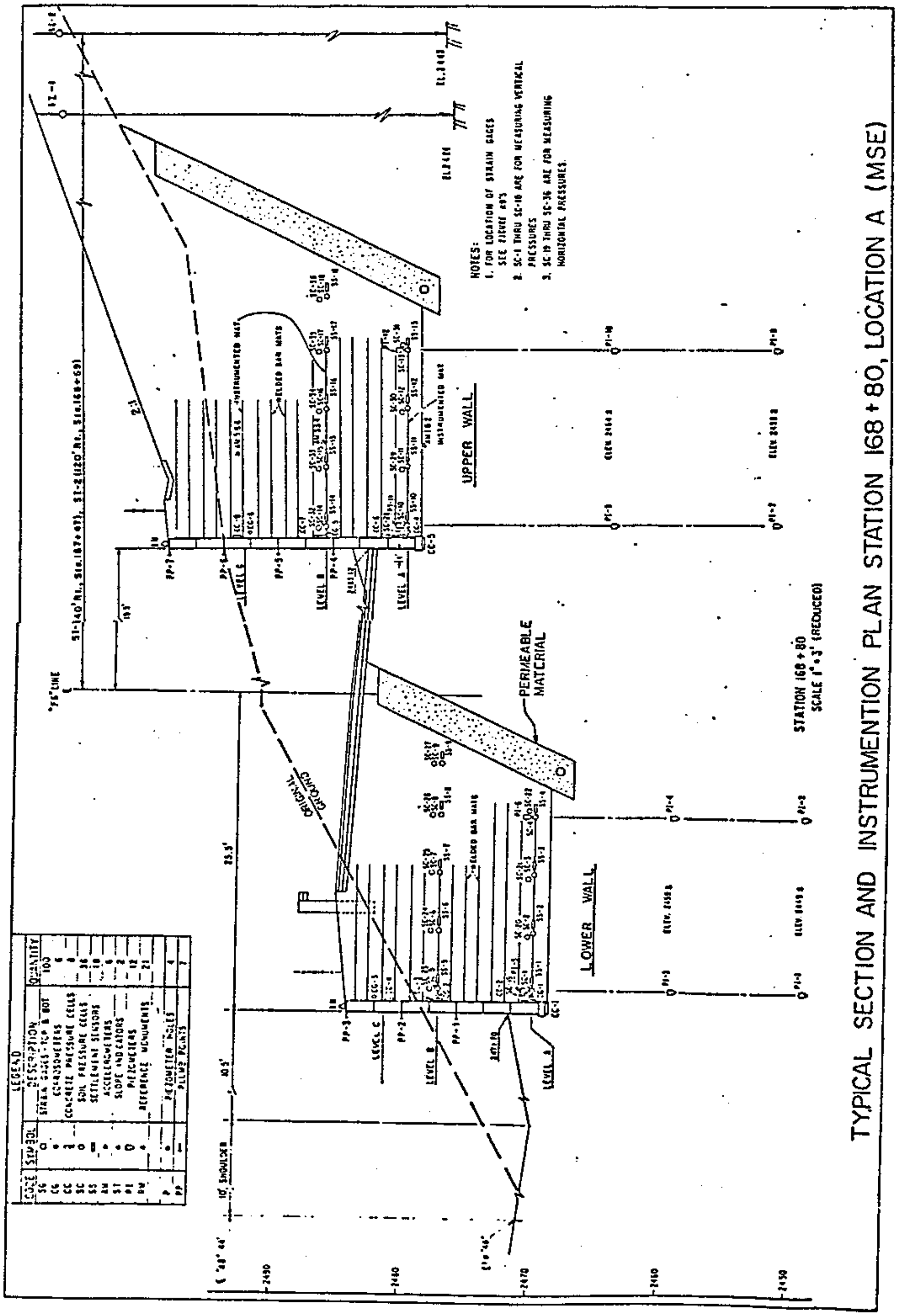
Figure 1B



LEGEND			
CODE	SYMBOL	DESCRIPTION	QUANTITY
SG	□	STRAIN GAGES - TOP & BOT	26
SC	○	SOIL PRESSURE CELLS	20
CC	▯	CONCRETE PRESSURE CELLS	4
CG	⌀	CORROSOMETERS	6
RM	Δ	REFERENCE MONUMENTS	8
PP	⊢	PLUMB POINTS	4
EX	⊢	EXTENSOMETERS	8
SP	⊥	SETTLEMENT PLATFORMS	10
AN	x	EXTENSOMETER ANCHOR	5
AM	↔	ACCELEROMETERS	8

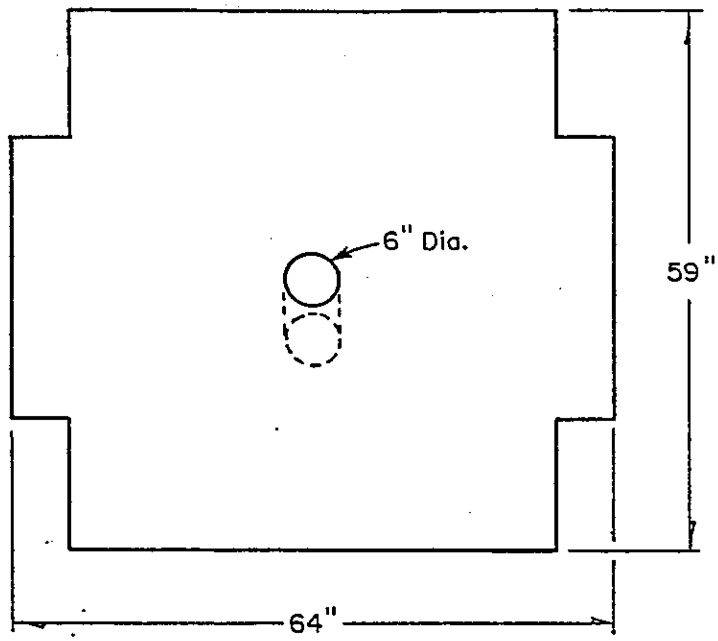
TYPICAL SECTION AND INSTRUMENTATION PLAN
REINFORCED EARTH WALL LOCATION B

Figure 2B

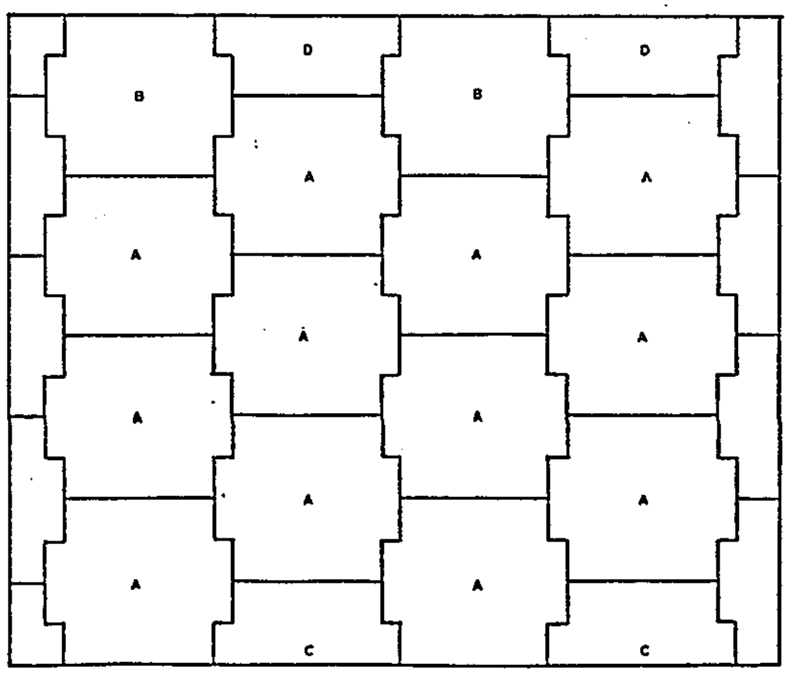


TYPICAL SECTION AND INSTRUMENTION PLAN STATION 168+80, LOCATION A (MSE)
UPPER WALL
LOWER WALL
PERMEABLE MATERIAL
ORIGINAL GROUND
WELDED BAR MATS
INSTRUMENTED MAT
STATION 168+80
LEGEND

Figure 3B



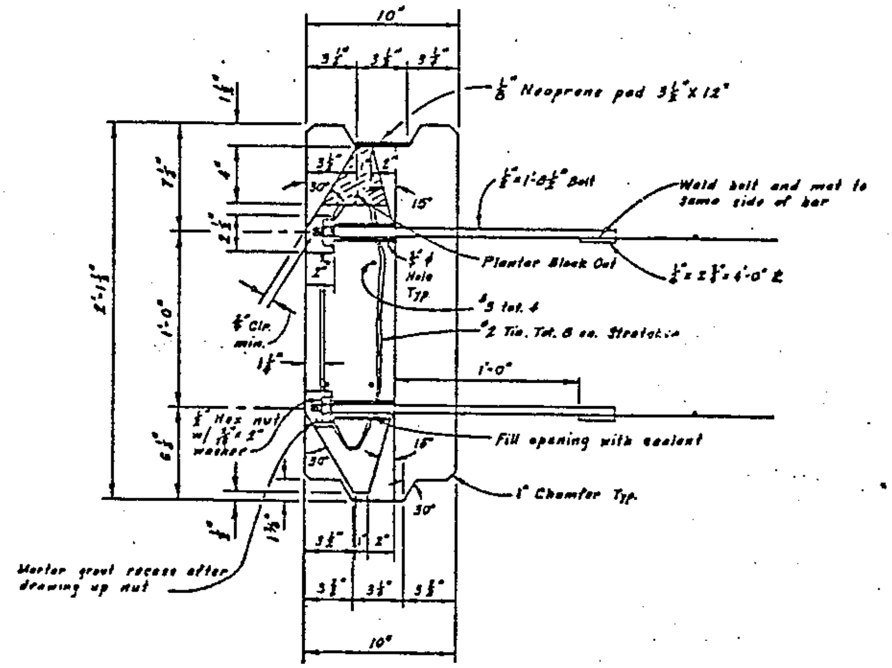
TYPICAL FULL PANEL
(A)



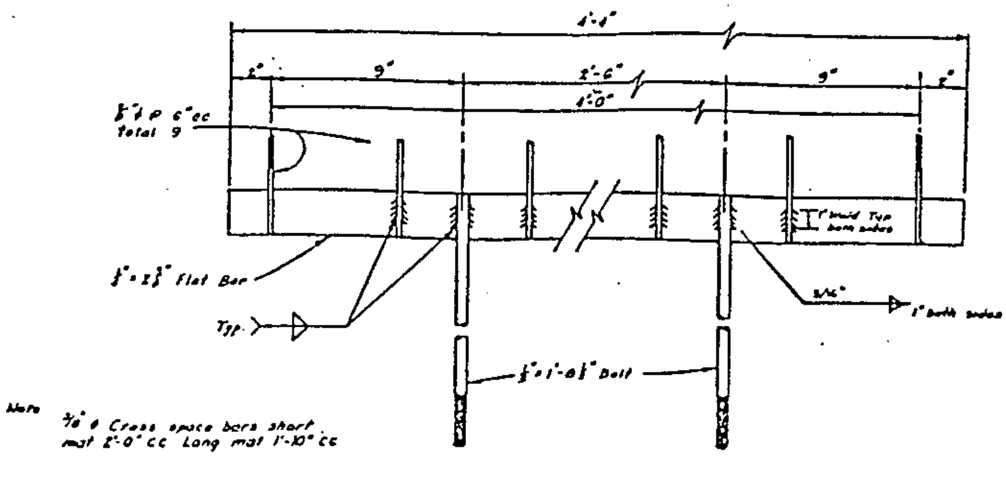
TYPICAL PANEL LAYOUT
(B)

REINFORCED EARTH FACING PANELS

Figure 4B



SECTION
Scale: 2" = 1'-0"



PLAN - BOLT CONNECTOR
Scale: 3" = 1'-0"

MECHANICALLY STABILIZED EMBANKMENT CONNECTION DETAIL

Figure 5B